Search for a two-Higgs-boson doublet using a simplified model in pp¯ collisions at s√=1.96 TeV

CDF Collaboration ; et al ; Canelli, F ; Kilminster, B

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We present a search for new particles in an extension to the standard model that includes a heavy Higgs boson (H^0), a lighter charged Higgs boson ($H^\pm$), and an even-lighter Higgs boson h^0, with decays leading to a W-boson pair and a bottom-antibottom quark pair in the final state. We use events with exactly one lepton, missing transverse momentum, and at least four jets in data corresponding to an integrated luminosity of 8.7 fb^{-1} collected by the CDF II detector in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV. We find the data to be consistent with standard model predictions and report the results in terms of a simplified Higgs-cascade-decay model, setting 95% confidence level upper limits on the product of cross-section and branching fraction from 1.3 pb to 15 fb as a function of H^0 and $H^\pm$ masses for $m_h^0 = 126$ GeV/c^2.

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The study of the mechanism of electroweak-symmetry breaking is one of the major thrusts of the experimental high-energy-physics program. Following the discovery of a Higgs-like boson at ATLAS [1] and CMS [2] with a mass of approximately 126 GeV/c^2 and complementary evidence from CDF and D0 [3], the most pressing question is whether this state is in fact the Higgs boson of the standard model (SM), part of an extended Higgs sector (such as that of the minimal supersymmetric standard model, MSSM [4]), a composite Higgs [5], or a completely different particle with Higgs-like couplings (such as a radion in warped extra dimensions [6] or a dilaton [7]).

We search for particles in an extension to the standard model that includes a light neutral Higgs boson, h^0, with

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mass $m_{h^0} = 126$ GeV$/c^2$. Rather than assuming a particular theoretical framework (such as the MSSM), we follow a phenomenological approach, using a general two-Higgs doublet model as a convenient simplified model [8], which contains a heavy charged Higgs boson $H^\pm$ and a heavier neutral state H^0. In this approach, the search for a number of specific final states that have the strongest couplings to Higgs particles is motivated [9, 10]. The final state of a W-boson pair (WW) is enhanced by WW scattering in models where the Higgs sector is strongly coupled [11]. This signal has been the subject of much detailed investigation [12]. The phenomenology of resonant production of the final states Zh^0 [13] and W^+W^-Z [14] has also been investigated.

In this letter, we focus on the final state $W^+W^-b\bar{b}$ [15], which can have a large production rate from the process $gg \to H^0$ followed by $H^0 \to H^\pm W^\mp$ with $H^\pm \to W^\pm h^0 \to W^\pm b\bar{b}$. The $W^+W^-b\bar{b}$ final state is also the final state of top-quark pair production, and has been extensively studied. However, no search for Higgs-boson cascades as described here has been reported previously, though searches have been performed for charged Higgs bosons in top-quark decays $t \to H^\pm b$ [16–18].

We analyze a data sample corresponding to an integrated luminosity of 8.7±0.5 fb^{-1} recorded by the CDF II detector [19], a general purpose detector designed to study $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV in the Fermilab Tevatron collider. The CDF tracking system consists of a silicon microstrip tracker and a drift chamber that are immersed in a 1.4 T axial magnetic field [20]. Projective-tower-geometry electromagnetic and hadronic calorimeters surrounding the tracking system measure particle energies, with muon detection provided by additional drift chambers located outside the calorimeters.

The signature of $H^0 \to W^\mp H^\pm \to W^-W^+h^0 \to W^-W^+b\bar{b}$ is a charged lepton (e or μ), missing transverse momentum, two jets arising from b quarks, and two additional jets from a W-boson hadronic decay. Events are selected online (triggered) by the requirement of an electron (e) or muon (μ) candidate [21] with transverse momentum p_T [22] greater than 18 GeV$/c$. After trigger selection, events are retained if the electron or muon candidate has a pseudorapidity $|\eta| < 1.1$ [22], $p_T > 20$ GeV$/c$, and satisfies the standard CDF identification and isolation requirements [21]. We reconstruct jets in the calorimeter using the JETCLU [23] algorithm with a clustering radius of 0.4 in $\eta - \phi$ space. The jets are calibrated using the techniques outlined in Ref. [24]. At least four jets are required, each with transverse energy $E_T > 15$ GeV and $|\eta| < 2.4$. Missing transverse momentum [25] is reconstructed using calorimeter and muon information [21]; in the $W^+W^-b\bar{b}$ experimental signature, the missing transverse momentum is mostly due to the neutrino from the leptonically-decaying W boson. We require $\not{E}_T > 20$ GeV$/c$. Since such a signal would yield two jets originating from b quarks, we require (with minimal loss of efficiency) evidence of decay of a b hadron in at least one jet. This requirement, called b-tagging, makes use of the SECVTX algorithm, which identifies jets from b quarks via their secondary vertices [26].

We model the production of H^0 bosons with $m_{H^0} =$ 325–1100 GeV$/c^2$ and subsequent decays $H^0 \to W^\mp H^\pm$ with $m_{H^\pm} =$ 225–600 GeV$/c^2$ and decays $H^\pm \to W^\pm h^0$ with $m_{h^0} = 126$ GeV$/c^2$, all with MADGRAPH [27]. Additional radiation, hadronization, and showering are described by PYTHIA [28]. The detector response for all simulated samples is modeled by the GEANT-based CDF II detector simulation [29].

The dominant SM background to this signature is top-quark pair production. We model this background using PYTHIA with a top-quark mass $m_t = 172.5$ GeV$/c^2$ [30]. We normalize the $t\bar{t}$ background to the theoretical calculation at next-to-next-to-leading order (NNLO) in the strong interaction coupling constant, α_s [31]. In addition, events generated by a next-to-leading order program, MC@NLO [32] are used in estimating an uncertainty in modeling the radiation of an additional jet.

The second largest SM background process is the associated production of a W boson and jets. Samples of W-boson+jets events with light- and heavy-flavor (b, c) quark jets are generated using ALPGEN [33], and interfaced with a parton-shower model from PYTHIA. The W-boson+jets samples are normalized to the measured W-boson-production cross section, with an additional multiplicative factor for the relative contribution of heavy- and light-flavor jets, following Ref. [26].

Backgrounds due to production of a Z boson with additional jets, where the second lepton from the Z-boson decay is not reconstructed, are small compared to the W-boson background and are modeled using events generated with ALPGEN interfaced to the parton-shower model from PYTHIA. The multi-jet background, in which a jet is misreconstructed as a lepton, is modeled using events triggered on jets and normalized to a background-dominated region at low missing transverse momentum where the multi-jet background is large.

The SM backgrounds due to production of single top quarks and pairs of vector bosons are modeled using MADGRAPH interfaced with PYTHIA parton-shower models and PYTHIA, respectively, and normalized to next-to-leading-order cross sections [34, 35].

The Higgs-boson candidate mass reconstruction begins with identification of the leptonically-decaying W boson, assuming the missing transverse momentum is due to the resulting neutrino. Of the multiple solutions for the neutrino pseudorapidity, we use the smallest value that yields the reconstructed W mass closest to the known value. The hadronically-decaying W boson is identified as the pair of jets that yield the reconstructed dijet mass closest to the known W mass, excluding jets with a b-tag. If fewer than two jets without b-tags are present, the same procedure is used but modified to include the b-tagged

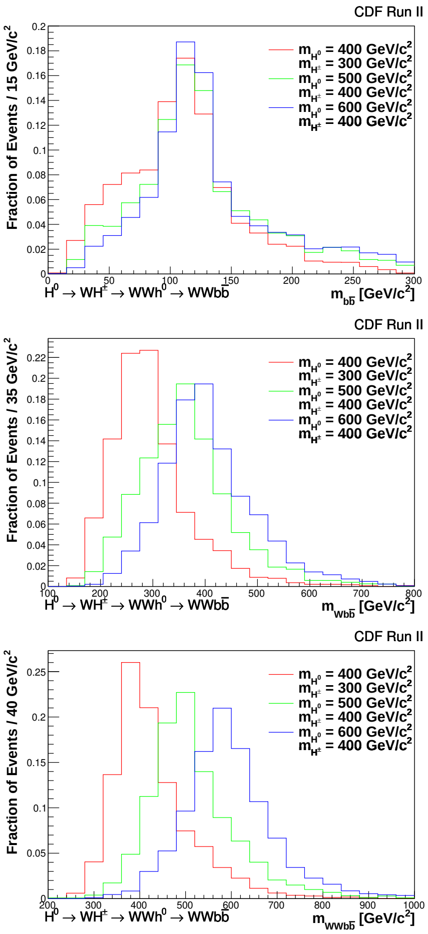

FIG. 1: Distribution of reconstructed Higgs-boson masses in simulated events. Top: $m_{h^0} = 126$ GeV/c^2 reconstructed as m_{bb}, center: $m_{H^\pm}$ as m_{Wbb}, and bottom: m_{H^0} as m_{WWbb}.

jets. The light h^0 is reconstructed from the remaining b-tagged jets. If fewer than two b-tagged jets remain, the jet or jets with largest transverse momentum not associated with the hadronic W-boson decay are used instead, without significant loss of mass resolution. Figure 1 shows distributions of the reconstructed mass for several choices of Higgs masses.

We enhance the signal-to-background ratio through requirements on the mass of the $W^+W^-b\bar{b}$ and $W^\pm b\bar{b}$ systems, and search for an excess of events above expectations from backgrounds in event distributions versus the mass of the $b\bar{b}$ system ($h^0 \to b\bar{b}$). Backgrounds have broad, smoothly decreasing distributions while a signal would be reconstructed near the Higgs-boson mass.

We consider several sources of systematic uncertainty on the predicted background rates and distributions, as well as on the expectations for a signal. Each systematic uncertainty affects the expected sensitivity to a signal, expressed as an expected cross-section upper limit in the no-signal assumption. The dominant systematic uncertainty is the jet-energy-scale uncertainty [24], followed by theoretical uncertainties on the cross sections of the background processes. To probe the description of additional jets, we compare our nominal $t\bar{t}$ model to one generated by MC@NLO and take the full difference as a systematic uncertainty. We also consider systematic uncertainties associated with the description of initial- and final-state radiation [36], uncertainties in the efficiency of reconstructing leptons and identifying b-quark jets, and uncertainties in the contribution from multiple interactions. In addition, we consider a variation of the Q^2 scale of W-boson+jet events in ALGPEN. In each case, we treat the unknown underlying quantity as a nuisance parameter. Except in the case of the normalization uncertainty, which affects only the overall rates, for each source of uncertainty we measure the distortion of the $m_{b\bar{b}}$ spectrum for positive and negative fluctuations of the underlying quantity. Table I lists the contributions of each of these sources of systematic uncertainty to the yields.

TABLE I: Contributions to the systematic uncertainty on the expected numbers of events for the two main background processes, the total background yield, and an example 500 GeV/c^2 Higgs-boson signal with an assumed total cross section of 1 pb.

Process	$t\bar{t}$	W-boson+jets	Total bg.	Higgs
Predicted yield	229	43	294	341
Jet energy scale	23%	-	17%	12%
Radiation	3%	-	2%	8%
Q^2 scale	-	18%	3%	-
Mult. interactions	1%	6%	2%	-
$t\bar{t}$ generator	5%	-	4%	-
Normalization	10%	30%	16%	-
Total syst. uncert.	26%	35%	24%	15%

We validate our modeling of the SM backgrounds in four background-dominated control regions. Each control region preserves the one lepton and at least four jet requirements with additional requirements per region. Events in the first region are used to study the $W^+W^-b\bar{b}$ and $W^\pm b\bar{b}$ mass reconstruction, requiring at least one b-tagged jet and $b\bar{b}$ mass smaller than 100 GeV/c^2. The second region probes $b\bar{b}$ and $W^+W^-b\bar{b}$ mass reconstruction, requiring at least one b-tagged jet and $W^\pm b\bar{b}$ mass smaller than 250 GeV/c^2. The third region tests the modeling of $W^\pm b\bar{b}$ and $b\bar{b}$ mass reconstruction, requiring at least one b-tagged jet and $W^+W^-b\bar{b}$ mass less than 450 GeV/c^2. The fourth region tests the modeling of the W-boson-plus-jets background, requiring exactly zero b-tagged jets and $W^+W^-b\bar{b}$ mass greater than 450 GeV/c^2. Assuming an H^0 production cross section of 250 fb, each control region is expected to have negligible signal contamination, with the exception of the zero b-tag region which would include signal events at approximately 10% of the sample. For two of the control regions, Fig. 2 shows the reconstructed $b\bar{b}$ mass distributions which, along with other similar distributions, indicate that the background

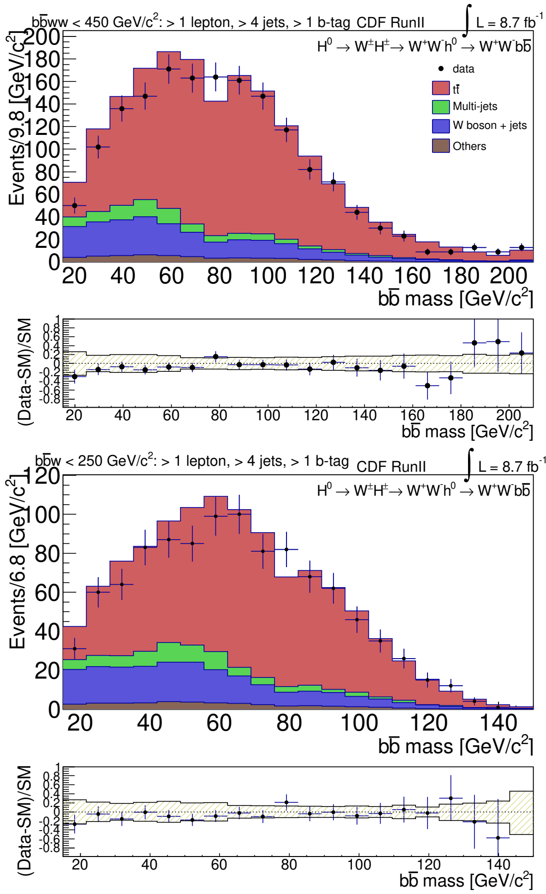

FIG. 2: Distribution of events versus reconstructed $b\bar{b}$ invariant mass ($m_{b\bar{b}}$) for observed data and expected backgrounds in two control regions. Top, control region consisting events with at least four jets, exactly zero b-tags and $m_{WWbb} < 450$ GeV/c^2. Bottom, control region consisting of events with at least four jets and $m_{Wbb} < 250$ GeV/c^2. The lower panels give the relative difference between the observed and expected distributions; the hatched areas show the combined statistical and systematic uncertainties of the expected background. The small dip near 80 GeV/c^2 is mainly due to the W-boson mass reconstruction.

mass distributions are well modeled within systematic uncertainties.

Figure 3 shows the observed distribution of events in a representative signal region compared to possible signals and estimated backgrounds. At each Higgs-boson mass hypothesis, we fit the most likely value of the Higgs-boson cross section by performing a maximum-likelihood fit in the binned $m_{b\bar{b}}$ distribution, allowing for systematic and statistical fluctuations via template morphing [37]. No evidence is found for the presence of Higgs-boson cascade decays in $WWb\bar{b}$ events. We set upper limits on Higgs production at 95% confidence level using the CLs method [38], without profiling the systematic uncertainties. The observed limits are consistent with expectation for the background-only hypothesis. See Fig. 4 and Table II.

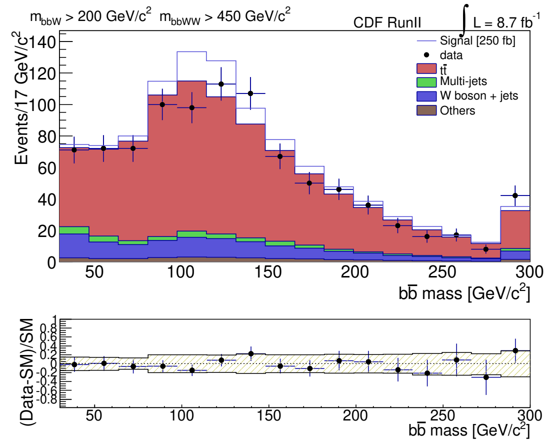

FIG. 3: Distribution of events versus reconstructed $b\bar{b}$ invariant mass ($m_{b\bar{b}}$), for observed data and expected backgrounds in the signal region. A signal hypothesis is shown, assuming a total cross section of 250 fb, $m_{H^0} = 500$ GeV/c^2, and $m_{H^\pm} = 300$ GeV/c^2. See Fig 2 for descriptions of lower panel and hatching.

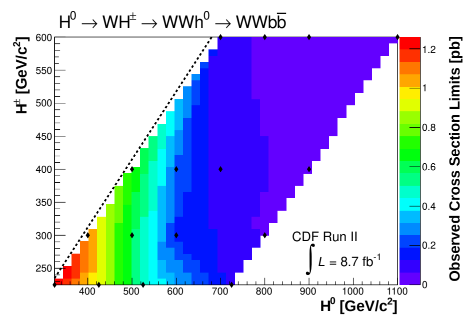

FIG. 4: Upper limits at 95% C.L. on the cross section times branching fraction as a function of the Higgs-boson masses $m_{H^\pm}$ and m_{H^0}; m_{h^0} is fixed to 126 GeV/c^2 in each case. Diamonds show the grid of probed masses; the intermediate values are interpolated.

In conclusion, we report on the first search for multiple Higgs bosons in cascade decays. For each accepted event, we reconstruct the lightest neutral Higgs-boson mass ($m_{b\bar{b}}$), and find the CDF data to be consistent with standard model background predictions. We calculate 95% C.L. upper limits on the cross section of such Higgs-boson production, assuming 100% branching ratio of H^0 to $W^\pm H^\mp$ and $H^\pm$ to $W^\pm h^0$, from 1.3 pb to 0.015 pb for masses ranging from ($m_{H^0} = 325, m_{H^\pm} = 225$) GeV/$c^2$ to ($m_{H^0} = 1100, m_{H^\pm} = 600$) GeV/$c^2$ respectively, and interpret the limits in terms of a simplified two-Higgs-doublet model. While the limits cited here do not exclude any region in the $m_{H^0} - m_{H^\pm}$-plane in the simplified model used, there are the first such limits available. The larger center-of-mass energy and integrated luminosity of data collected by the LHC experiments are likely to

TABLE II: Signal region definitions and expected and observed 95% C.L. upper limits on the production cross section times branching fraction for each Higgs-boson mass hypothesis. Theoretical predictions are also shown [39–41].

$(m_{H^0}, m_{H^\pm})$ (GeV/c^2)	$m_{H^\pm}$ (GeV/c^2)	m_{H^0} (GeV/c^2)	Exp (Obs) Limit (fb)	Theory (fb)
325, 225	> 175	> 275	1100 (1300)	34
400, 300	> 225	> 325	960 (1100)	18
425, 225	> 200	> 375	900 (960)	13
500, 300	> 200	> 450	470 (590)	3.9
500, 400	> 350	> 450	510 (700)	3.9
525, 225	> 100	> 500	420 (460)	2.5
600, 300	> 200	> 550	200 (180)	0.76
600, 400	> 350	> 550	210 (250)	0.76
700, 400	> 325	> 650	90 (100)	0.15
700, 600	> 450	> 650	10 (96)	0.15
725, 225	> 425	> 700	90 (120)	0.10
800, 300	> 275	> 750	50 (51)	3×10^{-2}
800, 600	> 475	> 725	43 (46)	3×10^{-2}
900, 400	> 450	> 775	28 (36)	6×10^{-3}
900, 600	> 475	> 800	24 (29)	6×10^{-3}
1100, 600	> 475	> 975	13 (15)	2×10^{-4}

have the sensitivity to discover or exclude such models.

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